

Equatorial Precession in the Control Software of the Ka-Band Object Observation and Monitoring Experiment

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Equatorial Precession in the Control Software of the Ka-Band Object Observation and Monitoring Experiment

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The Ka-Band Object Observation and Monitoring, or KaBOOM, project is designed mainly to track and characterize near Earth objects. However, a smaller goal of the project would be to monitor pulsars and study their radio frequency signals for use as a clock in interstellar travel. The use of pulsars and their timing accuracy has been studied for decades, but never in the Ka-band of the radio frequency spectrum. In order to begin the use of KaBOOM for this research, the control systems need to be analyzed to ensure its capability. Flaws in the control documentation leave it unclear as to whether the control software precesses coordinates from the J200 epoch. This experiment will examine the control software of the Intertronic 12m antennas used for the KaBOOM project and detail its capabilities in its “equatorial mode.” The antennas will be pointed at 4 chosen points in the sky on several days while probing the virtual azimuth and elevation (horizon coordinate) registers. The input right ascension and declination coordinates will then be converted separately from the control software to horizontal coordinates and compared, thus determining the ability of the control software to precess equatorial coordinates.

Nomenclature

d = Number of days since J2000 (including any fraction of a day)
 λ = Longitude
 φ = Latitude
LST = Local Sidereal time, in degrees
UT = Universal Time, in hours
 δ = Declination
 α = Right Ascension

I. Introduction

Although the Ka-Band Object Observation and Monitoring project primarily focuses on Near Earth Asteroids, it use of pulsar observations in the Ka band could expand this research subject immensely⁵. Pulsars are rotating and magnetized neutron stars that send out pulses within our line of sight of electromagnetic waves, found strongest in the radio frequency¹. The time of arrival (ToAs) from the brightest sources can be measured with a precision of about 100ns within an hour. Although the atomic clocks found in the rubidium and cesium frequency standards are much more accurate over the short term, pulsar frequency standards decay at a much slower rate². They also offer a clock source that is not terrestrial and that is based on macroscopic, instead of microscopic, objects. By using KaBOOM, operating in the Ka-Band, the study of these pulsars can be expanded.

In order to study pulsars, the KaBOOM antennas need to rely on the equatorial coordinate system, in addition to the horizontal system. The traditional coordinate system used by communication antennas is the horizontal system. It uses the elements of azimuth, the angular measurement of an object with reference to true north, and elevation, the angular measurement from the horizon⁴. These coordinates change for an object depending on location and time of day. However, astronomical objects are references via equatorial coordinates which include right ascension and declination. In order to imagine this, think of a traditional latitude and longitude coordinate system projected out as a sphere outside of the Earth. This sphere is stationary in reference to the constantly rotating Earth. Right ascension is comparable to latitude. It is an angular measurement of a sidereal object east (positive) or west (negative) of the vernal equinox line. Because of its relationship to sidereal time, it is given in hours instead of degrees. There are 24 hours of RA, each hour corresponding to 15°. Declination is similar to longitude, it is the angular measurement of the distance north or south of the celestial equator (our own equator projected out into space). Depending on location

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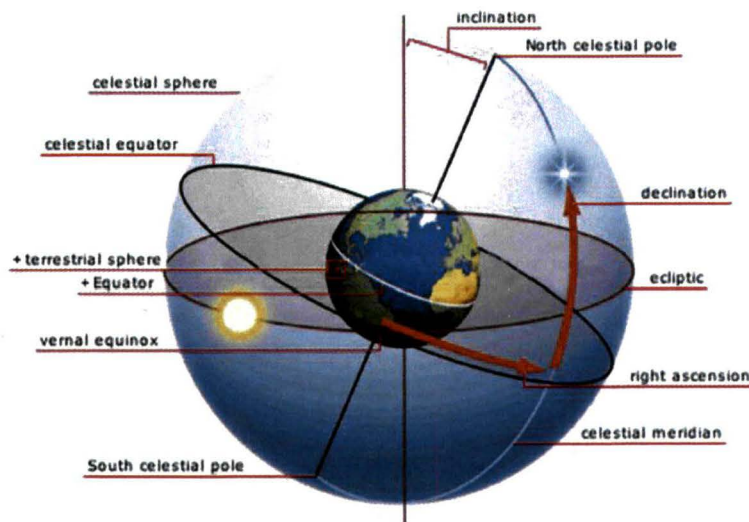


Figure 1: Celestial Coordinate System
 [Courtesy of <http://www.jtwastronomy.com/>]

GMT, with a similar definition for J1950. In order to compensate for the precession that occurs from the epoch, coordinates need to be precessed to what is called coordinates of date.

and time of day, the equatorial coordinates do not change. They move across the sky according to the rotation of the Earth. When the RA of the object is equal to the local sidereal time of your location, it will mean the star will be found on the meridian or the line going directly north to south.

Although RA and Dec do not change over a short amount of time, they are affected by precession: which is the small changes of the rotational axis of Earth³. Because of this, astronomers agree on standard locations of objects at certain times, called epochs. Most commonly, the epochs are given as J1950 and J2000. If a star's coordinates is said to be of epoch J2000, it means that the coordinates given correspond to its location on January 1, 2000 at 00:00

II. Experiment Details

A. Problem

The control software of the 12m Intertronic Antennas allow for KaBOOM to use both coordinate systems. It has the ability to track using either a set of time tagged coordinates in either horizontal or equatorial mode as well as to track a single equatorial mode coordinate as it crosses the sky. In order to do this, the control software continually converts the RA and Dec of an object according to the given location of the antenna and the time. However, there is a large issue with which type of RA and Dec are needed as the input coordinates. In several parts of the operations manual, the coordinates required by the system are noted as "RA and Dec, J2000" (p. 15,33), whereas on several other references of the equatorial coordinates note them as "precessed to date" (p. 42,52). This is a large discrepancy. Although coordinates will only change about 0.073 degrees from J2000, the small beam width (about 0.5 degrees) of the antennas requires the most accurate coordinates available. The value will also increase over the years that KaBOOM will be in use, and will need to be constantly accounted for to ensure long term accuracy of the equatorial pointing.

B. Experiment Procedure

To test the equatorial pointing of the antennas, an experiment will be conducted using the control interface of Antenna 2. It will be commanded to go into equatorial mode on several days to look at 4 arbitrary points in the sky. These points will all have the same RA, which will be associated with the local sidereal time at the time of the experiment. This is to ensure that we have a wide range of movements of the antenna. Although RA is typically given in hours, the control software only receives RA in degrees. We will then look at a Dec of -45° , 0° , 45° and 90° . This will give us a chance to look at points close to the equator as well as high in the sky. These points will all precess differently because of their location in reference to Earth's rotational axis. The most interesting point will be found using a Dec of 90° . Using an RA close to LST with this declination will always point the antenna directly at the North Star. This is the point located directly on the rotational axis of Earth and does not move relative to our location. Theoretically, pointing the antenna at this location should give a desired location with an azimuth of 0.00 , and an elevation equal to exactly the longitude of the antenna. For our purposes, this number was input as 28.5093°

for Antenna 2. The accuracy of the particular location is not important at the moment, since it is where the antenna thinks its pointing, rather than where it is actually pointing, that is most important for this experiment. This is because the pointing errors have yet to be determined on the KaBOOM antennas.

The experiment will be conducted with and without pointing corrections. Mainly determined by precise measurements of the antenna that have yet to be conducted, these corrections will help ensure future pointing accuracy. At the moment, these correction only account for the deviation of the axis from true vertical, the “axis tilt”. Before the experiment, it was unclear how these 2 components will change the output coordinates. The registers of the control system will allow us to enable/disable/corrections, set the coordinate input mode, and track a setpoint in the sky. A sample program mode is displayed in Fig. 1. For this test, the RA/Dec offsets were not used. The last 3 registers of the experiment detail registers needed to be read in order to complete the proper calculations. We choose the virtual axis registers to show where the antenna hopes to point. This is compared to the actual position of the antenna, which gives where the antenna is physically pointed. The time register is very important for comparison in projected azimuth and elevation calculations completed separately from the control software. There is an error of up to 10seconds between the reading of the virtual axis registers and the clock register. To help reduce this error, the reading can be taken from a control program provided by Intertronic. However, this will not give ms accuracy and rounds the time up to a tenth of a second.

R/W	Register Name	Address	Value	Comments
W	PowerSwitth	23384	1	Turns on Power to the Drives
W	CorrectionDisable	23391	1	Disable corrections
W	DataMode	23399	1	Equatorial mode
W	RADecDataSource	23401	0	Setpoint as data source (follows one RA/Dec value)
W	RAPosition	23406	#####	Value of RA: ###.####
W	DecPosition	23407	±#####	Value of Dec ±##.####
W	AZTrackStartTurn	23400	3	Auto (starts tracking with RA and Dec in reach)
W	RunControl	23385	1	Operate
R	CentralStatus	23383		Wait until Byte0, Bit2=0, All drives in operate
				Byte0, Bit3 = 0, Clock initialized
				Byte0, Bit4 = 0, SNTP requests replied to
W	RunMode	23386	4	Track
R	AzimuthMasterStatus	23683		Wait until all zeros: no errors or trips, axis locked
R	ElevationStatus	23703		Wait until all zeros: no errors or trips, axis locked
W	RAOffset	23408	#####	RA Offset ###.#### (optional)
W	DecOffset	23409	±#####	Dec Offset ±##.#### (optional)
W	RADecOffsetMode	23402	0/1	Disable/Enable Offsets
Data Registers to Read for Test:				
R	ElevationVirtualAxis	23608		All Virtual Axis gives the current values of the
R	AzimuthVirtualAxis	23588		position, updated every 4ms.
				Note: All read as ###.#### or ±##.####
R	SystemClockms	23435		System Clock, read in milliseconds

Figure 2: Sample Program for Equatorial Pointing Test

III. Results

Table 1 and 2 lists the register results of the experiment on July 16, 2013 (JD 2456489.5) and July 23, 2013 (JD 2456496.5). These sets of data were taken at an RA of 9h, or 135°. Table 1 uses the pointing corrections, but table 2 disables these corrections.

Inserted Coordinates:	RA = 9h	Dec = -45d
Time (ms)	Virtual AZ	Virtual EL
72506231 = 20:08:26.231	195.3194	14.0696
72551302 = 20:09:11.302	195.4615	14.0263
72586358 = 20:09:46.358	195.5062	13.9765

Inserted Coordinates:	RA = 9h	Dec = 0d
Time (ms)	Virtual AZ	Virtual EL
72729630 = 20:12:9.63	220.5356	54.4872
72749765 = 20:12:29.765	220.6073	54.4141
72770749 = 20:12:50.749	220.7776	54.3852

Inserted Coordinates:	RA = 9h	Dec = 45d
Time (ms)	Virtual AZ	Virtual EL
72900190 = 20:15:0.19	318.4946	65.4941
72922722 = 20:15:22.722	318.3559	65.4574
72945270 = 20:15:45.27	318.3001	65.3786

Inserted Coordinates:	RA = 9h	Dec = 90d
Time (ms)	Virtual AZ	Virtual EL
73048252 = 20:17:28.252	0.0019	28.5374
73073748 = 20:17:53.748	0.0019	28.5374
73100512 = 20:18:20.512	0.0019	28.5374

Table 1: July 18 Data, Corrections Enabled

Inserted Coordinates:	RA = 9h	Dec = -45d
Time (ms)	Virtual AZ	Virtual EL
72275900 = 20:04:35.900	199.3488	12.4191
72282900 = 20:04:42.900	199.3681	12.4105
72291900 = 20:04:51.900	199.3929	12.3996

Inserted Coordinates:	RA = 9h	Dec = 0d
Time (ms)	Virtual AZ	Virtual EL
72166300 = 20:02:46.300	226.5917	51.6817
72191200 = 20:03:11.200	226.7212	51.6150
72205200 = 20:03:25.200	226.7935	51.5775

Inserted Coordinates:	RA = 9h	Dec = 45d
Time (ms)	Virtual AZ	Virtual EL
71928400 = 19:58:48.400	315.9184	63.7687
72010300 = 20:00:10.300	315.6462	63.5589
72082600 = 20:01:22.600	315.4113	63.3731

Inserted Coordinates:	RA = 9h	Dec = 90d
Time (ms)	Virtual AZ	Virtual EL
72504200 = 20:08:24.200	360.0019	28.5058
72519200 = 20:08:39.200	360.0019	28.5058
72532200 = 20:08:52.200	360.0019	28.5058

Table 2: July 22 Data, Corrections Disabled

In order to compare our results with the desired outcome, we needed to convert the right ascension and declination to azimuth and elevation using the time, Julian date, and the location of the antenna. Time is first converted from milliseconds into hours and then used to create a precise Julian date. This is then put into an approximate calculate to determine the local sidereal time. Equation 1 below describes a reasonable estimate, which is within 0.3 seconds of time for dates within 100 years of J2000 (stargazing.net). All estimates of LST much occur between 0 and 360°.

$$LST = 100.46 + 0.985647d + \lambda + 15UT^{\dagger}$$

Equation 1: Calculating Local Sidereal Time

Once LST is calculated, it can be used calculate the hour angle alongside right ascension (α), shown in Equation 2. From here, the hour angle can be used alongside the latitude (ϕ), and declination (δ) to find the azimuth and elevation, shown in Equations 3 and 4

$$HA = LST - 15\alpha$$

Equation 2: Calculating hour angle

$$\cos az = \sin \phi \sin \delta + \cos \phi \cos \delta \cos HA^{\ddagger}$$

Equation 3: Calculating Azimuth

$$\sin el = \frac{\sin \delta - \sin az \sin \phi}{\cos az \cos \phi}$$

Equation 4: Calculating Elevation

After these are coordinated for the first set of data, they are then precessed as if they were J2000 coordinates. For this, a calculator create by Robert Ayers[§]. was used. This calculator has a time resolution of a year. The procedure of conversion is then repeated for the precessed to date coordinated with the same time and date values as the “J2000” coordinates.

[†] <http://aa.usno.navy.mil/faq/docs/GAST.php>, <http://www.stargazing.net/kepler/altaz.html>

[‡] <http://infohost.nmt.edu/tcc/help/lang/python/examples/sidereal/ims/AltAz-raDec.html>

[§] <http://www.robertmartinayers.org/tools/coordinates.html>

NASA USRP – Internship Final Report

Inserted:	RA = 9h	Dec = -45d				
Precessed (2000:2013)	RA = 9h 0m 28s	Dec = -44° 48' 14"				
Time (ms)	Virtual AZ (°)	Virtual EL (°)	Inserted AZ (°)	Inserted AZ Error (°)	Inserted EL (°)	Inserted EL Error (°)
72506231	195.3194	14.0696	195.3439	0.0245	13.9722	-0.0974
72551302	195.4615	14.0263	195.4734	0.0119	13.9282	-0.0981
72586358	195.5062	13.9765	195.5740	0.0678	13.8937	-0.0828
Inserted:	RA = 9h	Dec = 0d				
Precessed (2000:2013)	RA = 9h 0m 40s	Dec = -0° 3' 5"				
Time (ms)	Virtual AZ (°)	Virtual EL (°)	Inserted AZ (°)	Inserted AZ Error (°)	Inserted EL (°)	Inserted EL Error (°)
72729630	220.5356	54.4872	220.5690	0.0334	54.4342	-0.0530
72749765	220.6073	54.4141	220.6875	0.0802	54.3860	-0.0281
72770749	220.7776	54.3852	220.8108	0.0332	54.3357	-0.0495
Inserted:	RA = 9h	Dec = 45d				
Precessed (2000:2013)	RA = 9h 0m 52s	Dec = 44° 56' 55"				
Time (ms)	Virtual AZ (°)	Virtual EL (°)	Inserted AZ (°)	Inserted AZ Error (°)	Inserted EL (°)	Inserted EL Error (°)
72900190	318.4946	65.4941	318.4131	-0.0815	65.4671	-0.0270
72922722	318.3559	65.4574	318.3227	-0.0332	65.4122	-0.0452
72945270	318.3001	65.3786	318.2328	-0.0673	65.3571	-0.0215
Inserted:	RA = 9h	Dec = 90d				
Precessed (2000:2013)	RA = 9h 0m 20s	Dec = 89° 55' 39"				
Time (ms)	Virtual AZ (°)	Virtual EL (°)	Inserted AZ (°)	Inserted AZ Error (°)	Inserted EL (°)	Inserted EL Error (°)
73048252	0.0019	28.5374	0.0000	-0.0019	28.5087	-0.0287
73073748	0.0019	28.5374	0.0000	-0.0019	28.5087	-0.0287
73100512	0.0019	28.5374	0.0000	-0.0019	28.5087	-0.0287

Table 3a: Results from 7/16/13 - Enabled Corrections, Inserted Coordinate Comparison

Inserted:	RA = 9h	Dec = -45d				
Precessed (2000:2013)	RA = 9h 0m 28s	Dec = -44° 48' 14"				
Time (ms)	Virtual AZ (°)	Virtual EL (°)	Prec AZ (°)	Prec AZ Error (°)	Prec EL (°)	Prec EL Error (°)
72506231	195.3194	14.0696	195.3298	0.0104	14.1845	0.1149
72551302	195.4615	14.0263	195.4599	-0.0016	14.1406	0.1143
72586358	195.5062	13.9765	195.5610	0.0548	14.1062	0.1297
Inserted:	RA = 9h	Dec = 0d				
Precessed (2000:2013)	RA = 9h 0m 40s	Dec = -0° 3' 5"				
Time (ms)	Virtual AZ (°)	Virtual EL (°)	Prec AZ (°)	Prec AZ Error (°)	Prec EL (°)	Prec EL Error (°)
72729630	220.5356	54.4872	220.2830	-0.2526	54.4869	-0.0003
72749765	220.6073	54.4141	220.4020	-0.2053	54.4391	0.0250
72770749	220.7776	54.3852	220.5257	-0.2519	54.3891	0.0039
Inserted:	RA = 9h	Dec = 45d				
Precessed (2000:2013)	RA = 9h 0m 52s	Dec = 44° 56' 55"				
Time (ms)	Virtual AZ (°)	Virtual EL (°)	Prec AZ (°)	Prec AZ Error (°)	Prec EL (°)	Prec EL Error (°)
72900190	318.4946	65.4941	318.5208	0.0262	65.6225	0.1284
72922722	318.3559	65.4574	318.4292	0.0733	65.5677	0.1103
72945270	318.3001	65.3786	318.3381	0.0380	65.5127	0.1341
Inserted:	RA = 9h	Dec = 90d				
Precessed (2000:2013)	RA = 9h 0m 20s	Dec = 89° 55' 39"				
Time (ms)	Virtual AZ (°)	Virtual EL (°)	Prec AZ (°)	Prec AZ Error (°)	Prec EL (°)	Prec EL Error (°)
73048252	0.0019	28.5374	359.9671	0.0310	28.5752	0.0378
73073748	0.0019	28.5374	359.9670	0.0311	28.5751	0.0377
73100512	0.0019	28.5374	359.9668	0.0313	28.5751	0.0377

Table 3b: Results from 7/16/13 - Enabled Corrections, Precessed Coordinate Comparison

Figures 3a and 3b show the results from the first round of testing on July 16th. On this set of data, corrections were enabled which allowed for the compensation of the small tilt angle of the azimuth axis. It was unclear if the correction would affect the virtual axis, since this is the software's desired position. These graphs lead to ambiguous results. Although the results found in 3a tend to lead towards the antenna not precessing the coordinates, especially within the azimuth, the precessed coordinates have small errors within the elevation. However, because of the large errors in the inserted coordinates, it is clear that the pointing corrections are changing the desired virtual axis.

Instead of repeating the experiment in the same exact manner on an different day, the corrections were disabled for the next round of observations. The results are listed in Figure 4a and 4b.

Inserted :	RA = 9h	Dec = -45d				
Precessed (2000:2013):	RA = 9h 0m 28s	Dec = -44° 48' 14"				
Time (ms)	Virtual AZ (°)	Virtual EL (°)	Inserted AZ (°)	Inserted AZ Error (°)	Inserted EL (°)	Inserted EI Error (°)
72275900	199.3488	12.4191	199.3478	-0.000955	12.4158	-0.003313
72282900	199.3681	12.4105	199.3671	-0.000964	12.4073	-0.003230
72291900	199.3929	12.3996	199.3919	-0.000962	12.3963	-0.003295
Inserted:	RA = 9h	Dec = 0d				
Precessed (2000:2013):	RA = 9h 0m 40s	Dec = -0° 3' 5"				
Time (ms)	Virtual AZ (°)	Virtual EL (°)	Inserted AZ (°)	Inserted AZ Error (°)	Inserted EL (°)	Inserted EI Error (°)
72166300	226.5917	51.6817	226.5897	-0.001992	51.6784	-0.003272
72191200	226.7212	51.6150	226.7187	-0.002538	51.6119	-0.003054
72205200	226.7935	51.5775	226.7910	-0.002499	51.5745	-0.002996
Inserted:	RA = 9h	Dec = 45d				
Precessed (2000:2013):	RA = 9h 0m 52s	Dec = 44° 56' 55"				
Time (ms)	Virtual AZ (°)	Virtual EL (°)	Inserted AZ (°)	Inserted AZ Error (°)	Inserted EL (°)	Inserted EI Error (°)
71928400	315.9184	63.7687	315.9110	-0.007410	63.7696	0.000917
72010300	315.6462	63.5589	315.6390	-0.007202	63.5599	0.000989
72082600	315.4113	63.3731	315.4038	-0.007453	63.3739	0.000804
Inserted:	RA = 9h	Dec = 90d				
Precessed (2000:2013):	RA = 9h 0m 20s	Dec = 89° 55' 39"				
Time (ms)	Virtual AZ (°)	Virtual EL (°)	Inserted AZ (°)	Inserted AZ Error (°)	Inserted EL (°)	Inserted EI Error (°)
72504200	360.0019	28.5058	0.0000	-0.001900	28.5087	0.002900
72519200	360.0019	28.5058	0.0000	-0.001900	28.5087	0.002900
72532200	360.0019	28.5058	0.0000	-0.001900	28.5087	0.002900

Figure 4a: Results from 7/23/13 - Disabled Corrections, Inserted Coordinate Comparison

Inserted :	RA = 9h	Dec = -45d				
Precessed (2000:2013):	RA = 9h 0m 28s	Dec = -44° 48' 14"				
Time (ms)	Virtual AZ (°)	Virtual EL (°)	Prec AZ (°)	Prec AZ Error (°)	Prec EL (°)	Prec EL Error (°)
72275900	199.3488	12.4191	199.3533	0.004452	12.6285	0.209422
72282900	199.3681	12.4105	199.3726	0.004542	12.6200	0.209501
72291900	199.3929	12.3996	199.3976	0.004665	12.6090	0.209434
Inserted:	RA = 9h	Dec = 0d				
Precessed (2000:2013):	RA = 9h 0m 40s	Dec = -0° 3' 5"				
Time (ms)	Virtual AZ (°)	Virtual EL (°)	Prec AZ (°)	Prec AZ Error (°)	Prec EL (°)	Prec EL Error (°)
72166300	226.5917	51.6817	226.3295	-0.262184	51.7450	0.063271
72191200	226.7212	51.6150	226.4590	-0.262158	51.6788	0.063774
72205200	226.7935	51.5775	226.5317	-0.261799	51.6415	0.063992
Inserted:	RA = 9h	Dec = 45d				
Precessed (2000:2013):	RA = 9h 0m 52s	Dec = 44° 56' 55"				
Time (ms)	Virtual AZ (°)	Virtual EL (°)	Prec AZ (°)	Prec AZ Error (°)	Prec EL (°)	Prec EL Error (°)
71928400	315.9184	63.7687	315.9856	0.067165	63.9279	0.159200
72010300	315.6462	63.5589	315.7100	0.063787	63.7184	0.159546
72082600	315.4113	63.3731	315.4717	0.060439	63.5327	0.159591
Inserted:	RA = 9h	Dec = 90d				
Precessed (2000:2013):	RA = 9h 0m 20s	Dec = 89° 55' 39"				
Time (ms)	Virtual AZ (°)	Virtual EL (°)	Prec AZ (°)	Prec AZ Error (°)	Prec EL (°)	Prec EL Error (°)
72504200	360.0019	28.5058	359.9611	-0.040786	28.5726	0.066848
72519200	360.0019	28.5058	359.9610	-0.040865	28.5726	0.066811
72532200	360.0019	28.5058	359.9610	-0.040934	28.5726	0.066778

Figure 4b: Results from 7/23/13 - Disabled Corrections, Precessed Coordinate Comparison

Figure 4a and 4b prove the need to disable the corrections. This has dramatically changed the results. Unlike the errors found in the enable correction observations, the errors found are consistent with each measurement. In the inserted, non-precessed, results the errors only account to a few thousandths of a degree. With the precessed

coordinates, the errors are much larger, reaching a tenth of a degree. From these numbers alone, it is clear that the antenna is tracking only the inserted coordinates and not precessing them within its software.

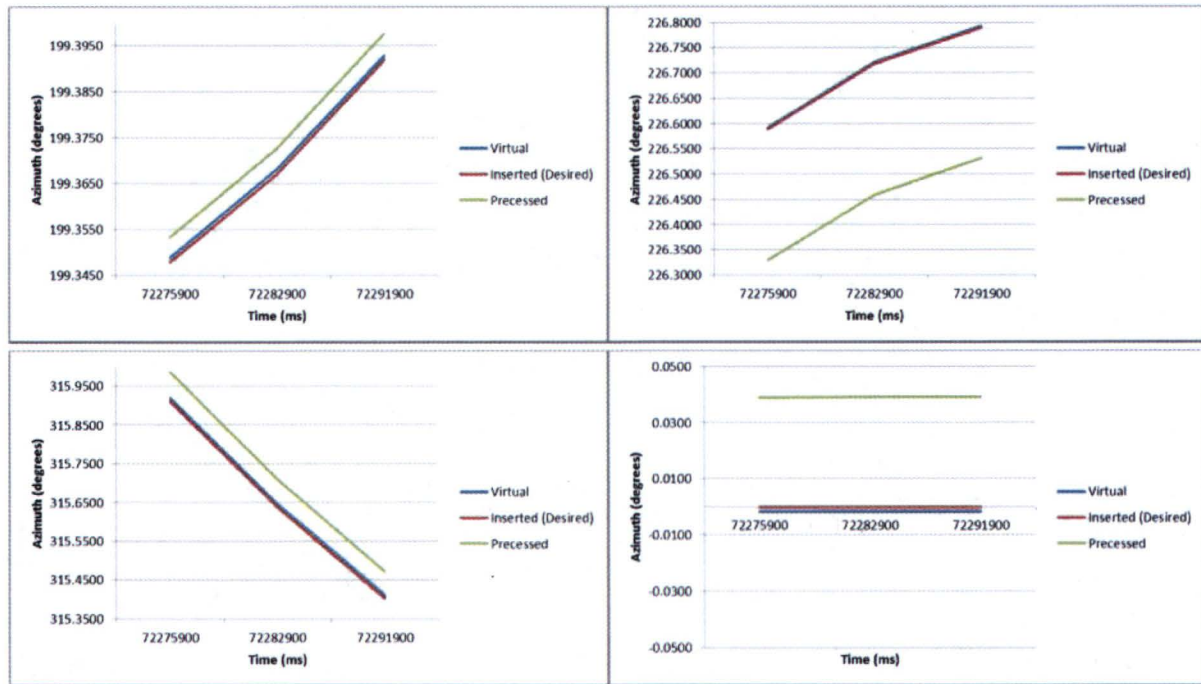


Figure 3a-d: Graphed results of the azimuth tracks of the 7/23/13 test. Going clockwise from the upper left: Dec = -45° , 0° , 45° and 90° .

To better visualize this result, Figure 3a-d shows a graphical representation of the azimuth track followed by the antenna (blue) alongside the proposed track of the inserted (red) and precessed (green) coordinates. In each case, the antenna is more closely following the inserted coordinate track.

IV. Conclusion

The Ka-Band Object Observation and Monitoring promise holds much promise to the future of radio astronomy. Not only will it help satisfy our ever growing need for survival by tracking near Earth asteroids, it will present a new wavelength to study pulsars. This new study can help create new standards for our clocks on Earth, and possibly standards of clocks for humans as they reach out into our Solar System. This small experiment has been first test to begin this study of pulsars. It is clear through the observations that the antenna control software needs an addition of precession algorithms in order to guarantee precise astronomical pointing. The data in this experiment has shown that the antenna is not currently precessing the coordinates to date. Seeing as the beam width is small, about half a degree, this could greatly limit the capabilities of the project. In order to verify the results, the experiment should be repeated several times over the next year. If given more time, the calculations could be improved upon to ensure accurate equatorial to horizontal coordinate conversions. More time could also give more clues as to how the control software of the antenna converts the coordinates. This is something that has yet to be researched but would be useful to help create better equatorial pointing accuracy.

However, equatorial pointing is just one facet of what needs to be done. KaBOOM's next steps also include calculating pointing offsets on the ground in addition to many other hardware and software aspects to allow it to overcome the difficulties of operating in the Ka band. This project has just begun and still has much time to go before it is operating on a scientific level. Through time, patience, and the hard work of the entire KaBOOM team, the radar array is sure to make leap and bounds in many aspects of space science. It has been an honor to be a small part of it.

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